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# THE REJUVENATION OF PROPERTIES IN TURBINE ENGINE HOT SECTION COMPONENTS BY HOT ISOSTATIC PRESSING

by

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National Aeronautical Establishment



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# THE REJUVENATION OF PROPERTIES IN TURBINE ENGINE HOT SECTION COMPONENTS BY HOT ISOSTATIC PRESSING

# LA REGÉNÉRESCENCE DES PROPRIÉTÉS DE PIÈCES DE TURBINE THERMIQUEMENT SOLLICITÉES PAR PRESSAGE ISOSTATIQUE À CHAUD


by/par

P.H. Floyd, W. Wallace, J-P.A. Immarigeon


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## ABSTRACT

A significant factor in the cost of ownership of industrial, marine and aircraft gas turbine engines is the high price of replacement of parts that have reached the limit of their original design life. Many parts, particularly those operating in the hot sections of gas turbine engines, will be replaced on a routine basis, even though they may have many thousands of safe operating hours remaining. In order to reduce costs, and to conserve materials that are rapidly becoming scarce, a great deal of effort is being expended to develop treatments that allow used parts to be refurbished and their original properties restored by regenerative heat treatments.

A significant development has occurred recently in this area with the introduction of hot isostatic pressing. With hot isostatic pressing it is possible to reheat-treat service exposed parts under pressure so that precipitate structures are restored, and internal defects such as creep voids and cavities are eliminated. As a result, new metal properties can be restored in many cases. However, during hot isostatic pressing there is a tendency for grain growth to occur, for changes in grain boundary structure to occur, and for irreversible changes in carbide morphology and distribution to occur. Consequently, the effective processing of materials requires that careful control of the time, temperature and pressure conditions used in the autoclave be achieved. The particular conditions used must be established for each individual alloy of interest in order to develop the appropriate microstructural features required and thereby obtain the desired improvements in mechanical properties.

This paper will review some of the Canadian work done in this area, with particular reference to a series of precipitation hardenable nickel base superalloys including Inconel alloy X-750, Udimet 500 and IN-738. The limitations of the process will be discussed as well as the successes achieved.




(français verso)

## RÉSUMÉ

Le coût élevé de remplacement de pièces dont la durée normale de vie est parvenue à échéance est un facteur important dans le coût d'opération de turbines à gaz industrielles, aéropropulsives ou navales.

On sait en effet que les pièces thermiquement sollicitées subissent en cours de service des transformations microstructurales qui affectent leurs propriétés et diminuent graduellement leurs performances, cette dégradation étant fonction des conditions de service. Ces pièces sont donc remplacées régulièrement selon des normes de vie sécuritaire pré-établies, alors que parfois, elles pourraient être encore utilisées sans risque.

De façon à réduire ce coût d'opération ainsi que la consommation de matériaux stratégiques, on cherche aujourd'hui à mettre au point des techniques qui permettraient de remettre en service des pièces déjà utilisées après regénérescence de leurs propriétés à l'état neuf.

Dans ce domaine, le traitement thermique par pressage isostatique à chaud offre des perspectives intéressantes. Grâce à ce procédé, il est possible de soumettre les pièces en question à des traitements thermiques sous pression, ce qui permet de régénérer les microstructures désirées tout en éliminant les défauts internes, tels les pores de fluage, introduits en cours de service. Dans bien des cas, on parvient ainsi à remettre ces pièces à neuf. Toutefois, au cours du traitement, la structure monocristalline peut être modifiée irréversiblement au dépens des propriétés désirées. Par exemple, le grain peut grossir ou la morphologie des joints de grains et des carbures qu'ils contiennent se modifier. Pour éviter cela, il est important de contrôler de façon adéquate les paramètres du traitement c'est à dire le temps, la température et la pression. Il est également important de déterminer les conditions nécessaires et particulières à chaque alliage impliqué.

Dans cet article, on résume les travaux récents effectués au Canada dans ce domaine. On rapporte en particulier des résultats impliquant une série de superalliages à base de nickel comprenant l'Inconel X-750, l'Udimet 500 et l'IN-738. On discute enfin du potentiel et des limites du procédé et on souligne les perspectives qu'offre cette nouvelle technique aux fabricants et utilisateurs de turbines à gaz.

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# THE REJUVENATION OF PROPERTIES IN TURBINE ENGINE HOT SECTION COMPONENTS BY HOT ISOSTATIC PRESSING

## 1.0 INTRODUCTION

The components used in the hot section of gas turbine engines incur damage in service that gradually degrades their mechanical properties and reliability. This service-induced deterioration depends on turbine operating conditions and may remain minimal for instance when turbines are only occasionally operated at full capacity. Nevertheless, once the original design lives of these components have been reached, the parts are normally replaced, even though they may be capable of further use.

The cost of replacement of these parts represents a significant factor in the cost of ownership of turbines. To reduce these costs, and also to conserve strategic materials, a great deal of effort is being expended to develop processes and regenerative heat treatments that will allow used parts to be refurbished and returned to service[1-6].

The incentives for extending service lives of these parts are considerable. For instance a typical row of blades in an industrial gas turbine may involve of the order of 60 to 75 blades, each of which may cost $800 to $1300, and therefore the total cost of replacement of a full row of blades may be as much as $100,000. In military aircraft or marine gas turbines, the replacement cost of hot section components may be just as high. The Canadian Armed Forces, for example, is currently faced with a $1 million expense to replace the turbine blades in the engines of a fleet of destroyers. When the engines were originally purchased, it was predicted that the low temperatures and stresses in the blades would ensure virtually unlimited life. Recently, however, a 9000 hours life limit has been imposed because of the service-induced precipitation of an embrittling phase. Work is being planned to determine the effects of this reaction on mechanical properties, and to investigate the possibility of reversing these effects by heat treatment.

In this paper, the nature of the service-induced damage in turbine blades and vanes is first identified and then discussed in terms of the type and operating conditions of the engines. The processes that can be used to rejuvenate properties in service-exposed parts are then considered. Emphasis is placed on hot isostatic pressing (HIP), a relatively new process which allows one to carry out heat treatments under high hydrostatic pressures. Some of the Canadian work done in this area is reviewed, and the limitations and prospects of HIP rejuvenation are discussed.

All of the data presented have been generated from components from large industrial gas turbines[7,8]. The components themselves are large and this allows one to prepare standard specimens for mechanical testing so that the condition of the blade material before and after rejuvenation can be properly characterized. The conclusions drawn from the results of this work may be extrapolated to deal with similar components from both aircraft and marine gas turbines since these exhibit the same general modes of deterioration in service.

## 2.0 TYPES OF SERVICE-INDUCED DAMAGE IN TURBINE BLADES AND VANES

During service, hot section components such as turbine blades and vanes may suffer both surface and internal damage.

Surface damage may be due to erosion, corrosion, oxidation, impact or thermal fatigue. For example, the inlet guide vane shown in Figure 1 exhibits both surface corrosion and thermal fatigue cracking in the trailing edge[9]. The alloy in this case is Udimet 500 a cast nickel-base superalloy. Its microstructure will be examined later.

Internal damage is related to microstructural changes which occur slowly during service depending on alloy composition and service operating conditions, and therefore to some extent on

the type of turbine. In this respect, there are perhaps two major differences between operating environments of industrial gas turbines and military aircraft or marine gas turbines. Firstly the land based power plants tend to operate for very long times under relatively stable conditions and therefore problems due to thermal fatigue are usually less severe. Secondly, industrial turbines are often operated on relatively clean fuel and in salt free atmospheres and therefore problems with oxidation and sulphidation also tend to be less severe than in marine gas turbines. However, these problems are not unknown as indicated by Figure 1.

This paper does not deal with the repair of surface damage, such as corrosion or surface connected fatigue cracks. It deals only with the elimination of internal microstructural damage. It also deals only with nickel-base superalloy components which account for a large proportion of the hot section of any turbine.

## 3.0 DETERIORATION OF MICROSTRUCTURE IN Ni-BASE SUPERALLOYS

The nickel-base superalloys are complex alloys and so are the changes in microstructure that occur in service. These alloys are strengthened by the precipitation of the intermetallic phase $Ni_3Al$ ($\gamma'$) in the grain interiors and by the precipitation of this phase and carbides along grain boundaries. Heat treatments for this type of alloy are carefully designed to achieve a proper balance between intragranular strength and grain boundary strength. These are controlled by the size, shape and distribution of the $\gamma'$ and carbide particles.

A typical microstructure is shown in Figure 2. In the alloy shown, the intermetallic phase exists as small cuboidal particles and as hyper-fine spheroidal particles. The grain boundary carbides are in the form of small discrete particles surrounded by a $\gamma'$ envelope. This type of microstructure is developed by a two stage heat treatment and provides high creep strength to the alloy. The coarser $\gamma'$ particles and $\gamma'$ envelope are formed during high temperature ageing, while the finer particles are precipitated during secondary ageing at a lower temperature. Some superalloys have grain boundaries that are in fact denuded of any $\gamma'$. In all cases, however, the presence of discrete carbides along grain boundaries ensures creep strength without serious loss of ductility.

During long time exposures under high stresses at high temperatures, various structural changes may occur. The $\gamma'$ particles will coarsen, generally according to a time to the 1/3 power growth law, and become overaged. The $\gamma'$ precipitates may also become elongated in the direction of loading, and grain boundary carbides will agglomerate to form continuous brittle films, as shown in Figure 3. Creep induced cavities may also form on grain boundaries aligned normal to the stress axis, as shown in Figure 4. Finally, brittle intermetallics such as sigma phase may also form occasionally, as shown in Figure 5. This is the microstructure of the Udimet 500 vane shown in Figure 1. The trailing edge cracking in this vane was due partly to the precipitation of these embrittling sigma platelets[9].

## 4.0 DETERIORATION OF MECHANICAL PROPERTIES

These microstructural changes are detrimental to properties such as strength, ductility and notch sensitivity. As pointed out previously, the changes will occur slowly depending on alloy composition and service operating conditions. It is difficult however to predict the rate of deterioration from first principles and in practice attempts are being made to monitor this experimentally.

Blades are removed from service and their stress-rupture properties are compared against their original properties. For example, residual stress-rupture properties in Inconel alloy X-750 blades from a engine with a turbine inlet temperature of 790°C are shown in Figure 6. The data indicate that properties of some of the blades are well below the original specification minimum of 100 hours at 345 MPa, in some cases as early as after 20,000 hours of service. The data cover three rows of blades and properties are quite scattered. The most severely damaged material is from row 3 which was the leading row and therefore the hottest of the three. By contrast, data for Inconel alloy 700, Figure 7, also from an engine with a turbine inlet temperature of 790°C, indicate that even after 50,000 hours of service many of the blades would still meet original specifications[10].

The data in Figure 6 were collected by Westinghouse Canada as part of a program intended to allow realistic assessment of remaining blade lives. The data are not necessarily typical and there may be considerable scatter from turbine to turbine, thus making it difficult to establish life limits without being unduly conservative.

## 5.0 REJUVENATION OF MECHANICAL PROPERTIES

Once the safe operating life of a set of blades has been exhausted, the blades can either be replaced at great expense or be rejuvenated. This requires an appropriate heat treatment that can regenerate acceptable precipitate structures and eliminate other internal damage. This might be done either by conventional heat-treatment or by hot isostatic processing, and these alternatives are considered in turn.

### (a) Rejuvenation by Conventional Heat-Treatment

Data from Westinghouse Canada for Inconel alloy X-750 blades indicate that original properties cannot be fully restored by conventional heat treatment. This is demonstrated in Figure 8[8]. The solid points in the figure represent stress-rupture properties for service-exposed blades tested by Westinghouse Canada. The lower hatched lines give the scatter band for similar material tested by Westinghouse Electric Corporation (U.S.A.)[11] while the upper hatched lines give the scatter band for material given conventional laboratory heat treatments[11]. It should be noted that the Westinghouse Canada tests were conducted at 345 MPa while the W.E.C. data resulted from tests at 310 MPa. The relatively large scatter. exhibited by both sets of data is probably due to variations in initial (new) material properties and differences in turbine operating conditions.

These data indicate quite clearly that, after long service exposures, it is not possible to restore properties completely by a conventional heat treatment. In reheat-treated blades, there is a steady decrease in properties as the original service life of the parts increases. This suggests that certain damage is introduced during service that cannot be eliminated by conventional heat treatments.

Of the types of damage that were discussed previously, the $\gamma'$ morphology changes should be reversible by conventional heat treatments involving complete solutioning followed by controlled ageing. The carbide morphology changes should also be reversible, but not so, however, if the initial carbide coarsening rate is controlled by the dissociation of primary carbides, that is carbides that are formed during solidification of the alloy. It is also unlikely that cavitation damage would be eliminated by a straight conventional heat treatment. Meanwhile, the precipitation of embrittling minor phases should be reversible. However, because of possible changes in elemental segregation, that might result from service exposure and from resolutioning of these phases, there is no assurance that they might not reform very rapidly once the parts are returned to service.

It should also be noted that during reheat treatment, irreversible changes in structure may occur that may be detrimental to part properties. It is possible for instance that grains could coarsen during complete solutioning and this might lower either intermediate temperature strength or ductility. The morphology of grain boundaries may also be modified during processing at the expense of both strength and ductility.

Thus, in the Inconel alloy X-750 blades under consideration, it would appear that the unrecovered damage, revealed by the data in Figure 8, may be in the form of creep cavities, elemental segregation, grain coarsening or modified grain boundary morphology.

### (b) Rejuvenation by Hot Isostatic Pressing

In this alternative treatment, the parts are exposed simultaneously to high temperature and high hydrostatic pressure. The autoclave at Westinghouse Canada, shown in Figure 9, is

typical of the units used for this type of treatment[7,8]. It consists of a cold steel wall pressure vessel containing a furnace with a 430 mm diameter by 1050 mm high working zone. The furnace is capable of temperatures up to 1230°C and of argon gas pressures up to 140 MPa. The high pressure is generated by two diaphragm compressors operated in series.

Numerous studies have shown that casting defects such as shrinkage cavities, hot tears or micropores can be eliminated from castings by hot isostatic pressing, and HIP densification has been demonstrated for a wide range of strategic materials including nickel-base superalloys[7,12-17]. For instance, it has been demonstrated that large shrinkage cavities can be closed in IN-738 turbine blade castings[7]. This is shown in Figure 10, which compares residual porosity in the blades before and after HIP densification. Therefore, one can expect HIP processing to be capable of closing creep voids in service exposed parts made from similar materials. The data in Figures 11 to 13 demonstrate that it is indeed possible to eliminate such damage using hot isostatic pressing while at the same time restoring suitable precipitate structures in Inconel alloy X-750 blades[8].

This is first shown in Figure 11 which compares stress-rupture properties of service-exposed and HIP processed blades against properties for commercially and laboratory heat-treated service-exposed parts as well as against average new blade properties. The heat treatment used in all these cases was a standard heat treatment for the alloy. The results, which cover material from several different sets of blades, clearly show that only in the case of HIP processed parts do properties approach those of new blades.

However, these data are rather limited since they provide information at only one temperature and one stress level. In order to gain confidence in HIP processing, broader ranges of temperature and stress, covering conditions experienced in service, need to be considered. This is done in Figure 12 which compares Larson-Miller plots for service-exposed and HIP processed Inconel alloy X-750 blades against properties for new material.

The HIP processed results fall near the centre of the scatterband for new material and they indicate that the properties are fully restored. Interestingly, even the service-exposed material data fall within this scatterband when testing is carried out under low stresses. This suggests that the rupture mechanism in this alloy becomes insensitive to microstructural changes and cavities at low stresses. However, internal microstructural damage appears to exert a pronounced effect at lower temperatures and higher stresses. Since the lowest temperature used in these tests (735°C) is higher than the actual service temperature for the Inconel alloy X-750 blades, these results demonstrate the importance of testing under conditions as close as possible to service conditions.

Finally, short term creep rupture data for service-exposed blades and HIP processed blades are shown in Figure 13 for three different stress/temperature levels. Under all testing conditions, the HIP processed material clearly exhibits slower secondary creep rates than service-exposed material. Furthermore, the onset of tertiary creep is appreciably retarded in the HIP processed material. It may also be noted that, as before, the differences between service-exposed and HIP processed material decreases as test temperature is increased.

## 6.0 MICROSTRUCTURAL CONTROL

The microstructures of the Inconel alloy X-750 blades before and after HIP processing are shown in Figure 14[8]. Before treatment, the $\gamma'$ particles are still spherical and only slightly coarsened, while the grain boundary carbides form continuous films. After treatment by HIP, the $\gamma'$ and carbides are refined and a $\gamma'$ precipitate free band appears at the grain boundary. This is a normal feature in this particular alloy and the HIP treated microstructure is comparable to that of new material.

Comparison of the microstructures in service-exposed blades and HIP processed blades also reveals that the grain size is the same in both materials (ASTM No. 3)[8]. Therefore improvements in

creep resistance, Figure 13, are not due to grain size effects and must be due to removal of other types of internal structural damage.

## 7.0 DISCUSSION

It has been shown that a standard heat-treatment used in conjunction with hot isostatic pressing is effective in restoring original properties in used Inconel alloy X-750 blades. However, there is evidence that this may not always be the case with other alloys and that subtle changes in heat treatment practice may be needed to achieve satisfactory results.

For instance, in the case of IN-738 blade castings, it has been shown previously that full solution treatment during HIP and post-HIP processing can degrade intermediate temperature stress-rupture properties[7,18]. In this work, the blades were processed using two different post-HIP thermal cycles. In one case, (HIP A), the blades were solution-treated and then air cooled prior to further heat treatment while in the second case, (HIP B), the blades were solution-treated and then furnace cooled directly to the primary ageing temperature.

When the stress-rupture lives of the two materials are compared, Figure 15, it is clear that only the second treatment can preserve original as-cast properties.

There is reason to believe that this difference is related to fine changes in grain boundary structure[18]. The two materials are almost identical in structure except that the material processed according to the first treatment (HIP A) has a smooth grain boundary while the other material (HIP B) has a finely serrated structure, as shown in Figure 16. It may not be widely appreciated that such fine details may be important in castings.

This is only one example of the need to design HIP thermal cycles very carefully, with the eventual service conditions of the material in mind. In practice, any microstructural modification that may be induced by HIP processing and that may be detrimental to part properties must be avoided. The problem is a complex one and requires a clear understanding of the material's response to heat treatment. It is not however within the scope of this work to discuss this matter. This is done elsewhere in detail[19].

It should also be noted that acceptable microstructural features and satisfactory test results after HIP rejuvenation are not sufficient to provide complete assurance that original properties are in fact fully restored. This is because the testing conditions can only approximate the service conditions and therefore test results cannot tell with any certainty whether the part deterioration will not be faster after return to service. Such assurance can only be provided in the end through real-time in-service monitoring of rejuvenated parts.

## 8.0 CONCLUSIONS

The data shown in this paper have been generated largely by Westinghouse Canada and this acknowledges the leading role they have played in this field in Canada.

The rejuvenation of used turbine parts is a promising field and contracts have been placed with Westinghouse to extend this type of work to other alloys. The work will include monitoring the in-service behaviour of rejuvenated parts on a real-time basis and it is hoped that this will generate confidence among users of gas turbine engines. And of course, it is hoped that the users of military gas turbines will consider this approach to turbine engine blade refurbishment.

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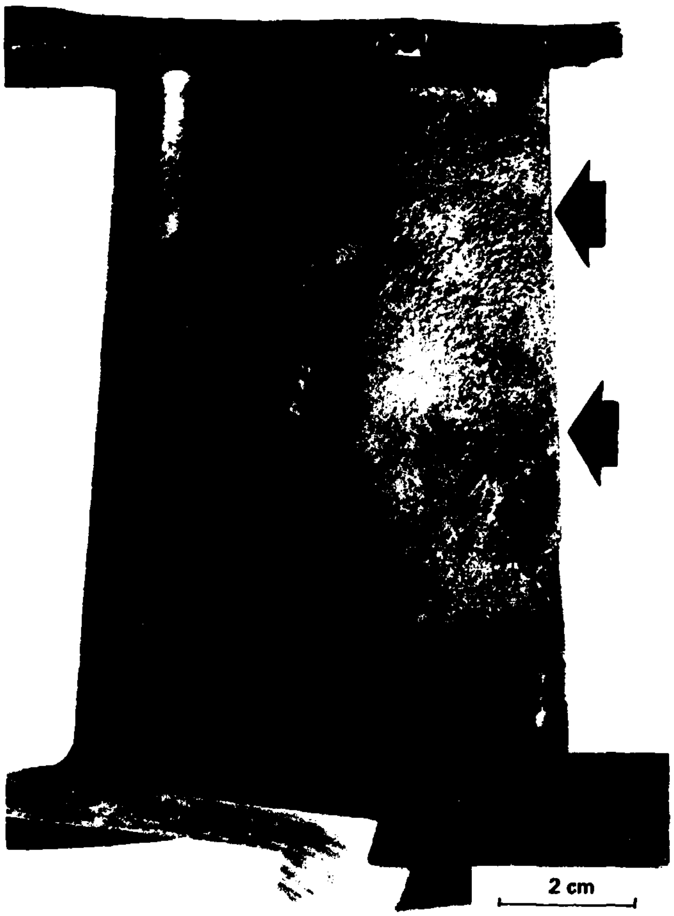


FIG. 1: SERVICE-EXPOSED UDIMET 500 VANE SHOWING TRAILING EDGE CRACKING AND SURFACE CORROSION[9]

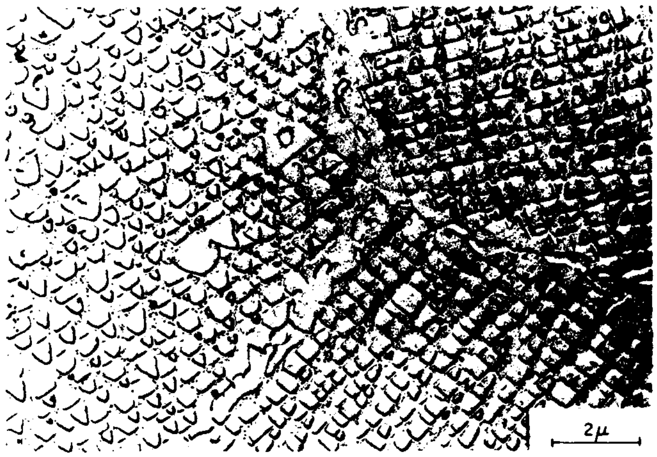


FIG. 2: THE BLOCKY AND SPHERICAL GAMMA-PRIME IN THE GRAIN INTERIORS AND THE DISCRETE GRAIN BOUNDARY CARBIDES SURROUNDED BY A GAMMA-PRIME ENVELOPE IN NEW MATERIAL

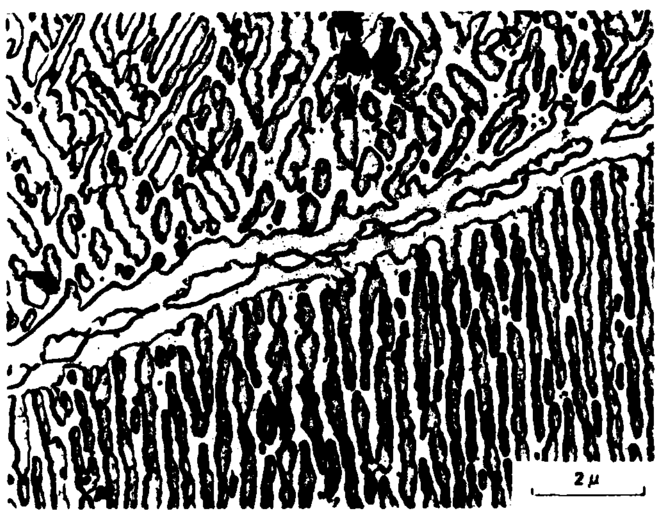


FIG. 3: COARSENED AND ELONGATED GAMMA-PRIME PARTICLES AND CONTINUOUS CARBIDE FILM ALONG A GRAIN BOUNDARY IN SERVICE-EXPOSED MATERIAL

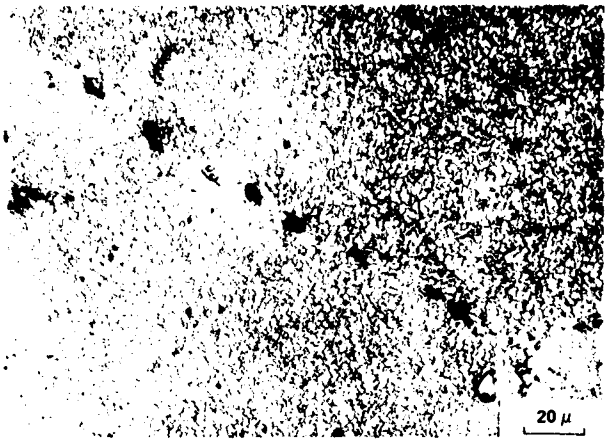


FIG. 4: CREEP INDUCED CAVITIES (STRESS AXIS VERTICAL)

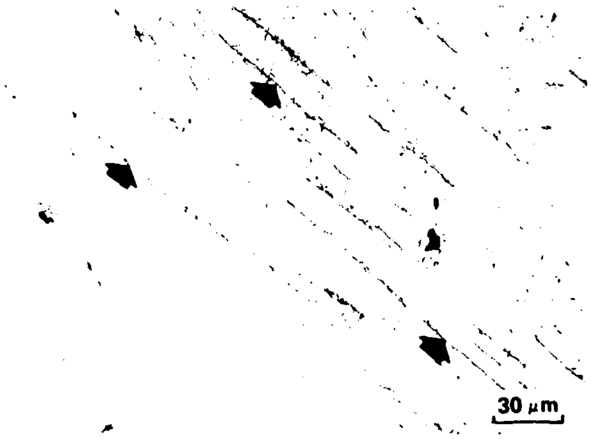


FIG. 5: THE PRECIPITATION OF SIGMA PHASE IN THE UDIMET 500 VANE SHOWN IN FIGURE 1[9]

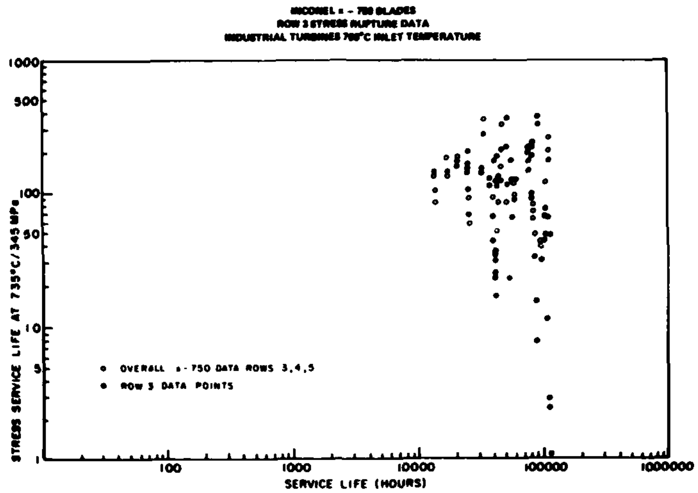


**FIG. 6: LIFE TREND FOR INCONEL ALLOY X-750, ROW 3 BLADES SHOWING A CRITICAL REDUCTION IN PROPERTIES AFTER APPROXIMATELY 100,000 HOURS[8,10]**

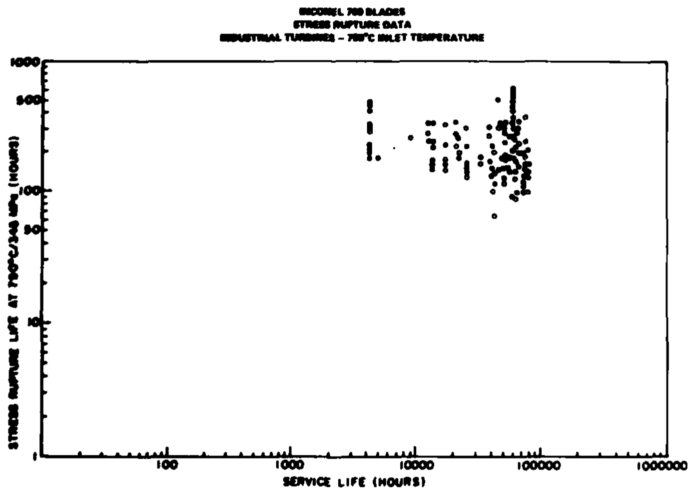


**FIG. 7: LIFE TREND CURVE FOR INCONEL ALLOY 700 BLADES[10]**

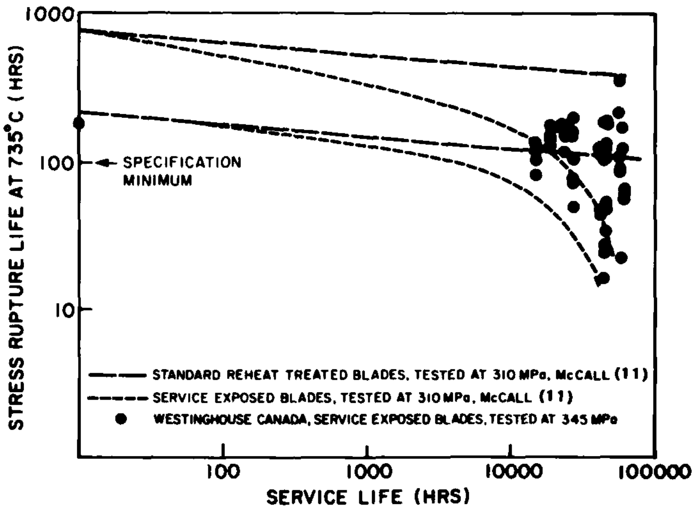


**FIG. 8: THE VARIATION OF REMAINING STRESS-RUPTURE LIFE AT 735°C WITH SERVICE TIME IN FORGED INCONEL ALLOY X-750 TURBINE BLADES[8]**

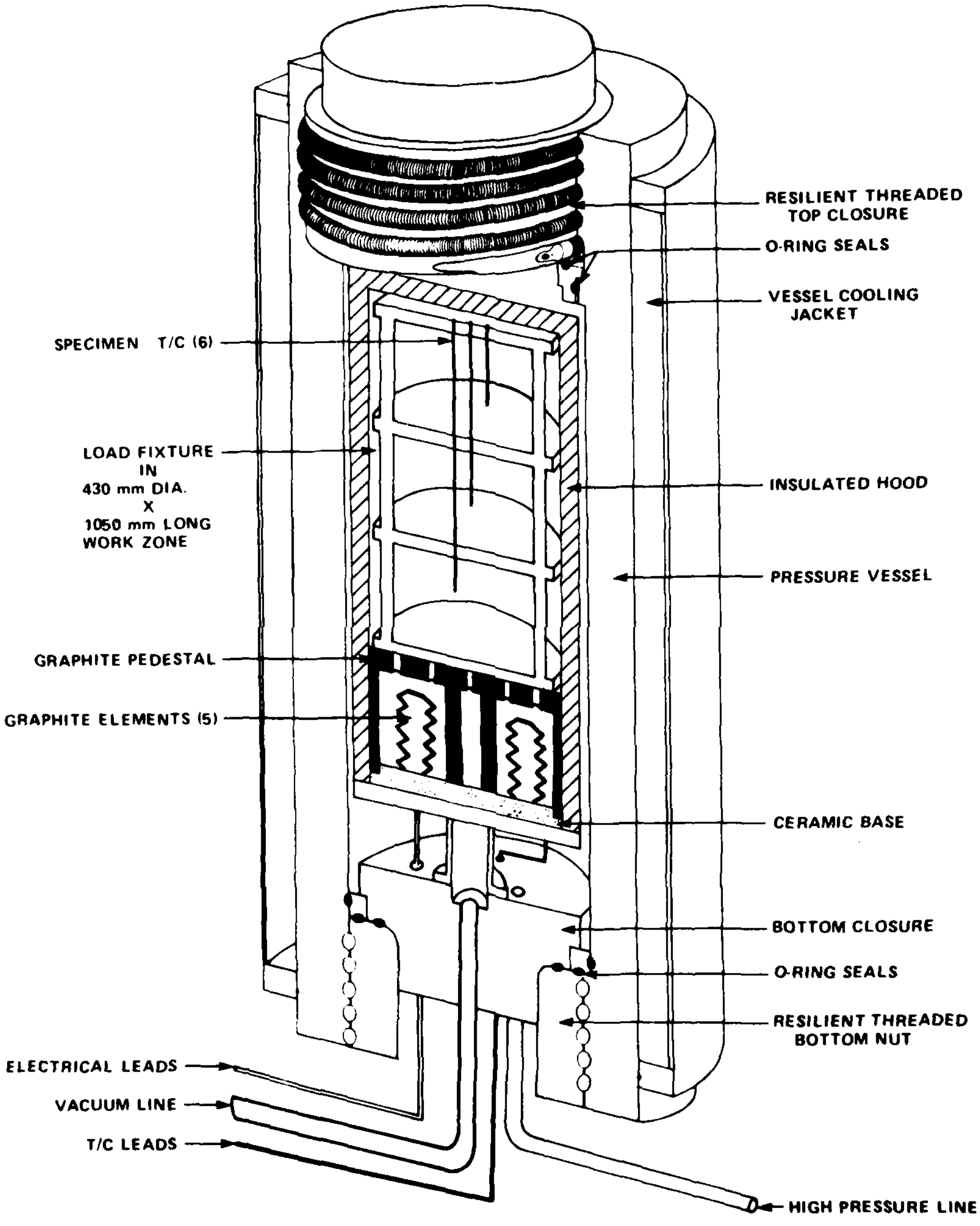


**FIG. 9: SCHEMATIC OF THE WESTINGHOUSE CANADA HIP VESSEL**

HEALING OF CASTING DEFECTS BY HOT ISOSTATIC PRESSING

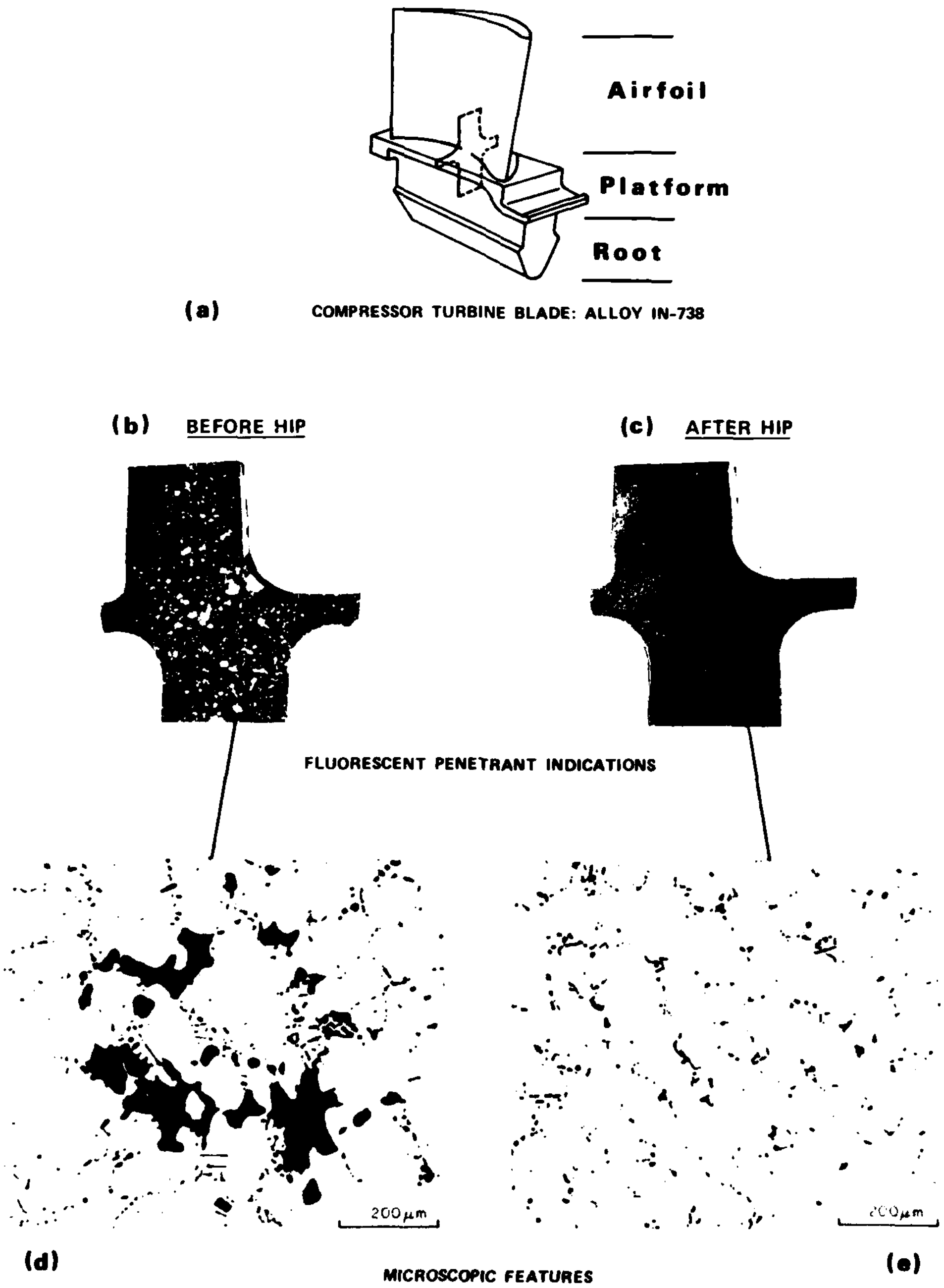


**FIG. 10: EFFECT OF HIP PROCESSING ON MICROPOROSITY IN AN INVESTMENT CAST TURBINE BLADE[7]**

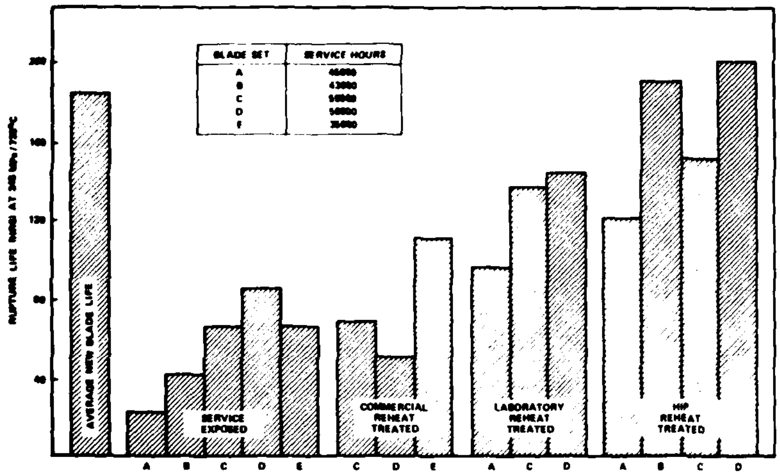


**FIG. 11: STRESS-RUPTURE PROPERTIES FROM SEVERAL SETS OF INCONEL ALLOY X-750 BLADES AFTER VARIOUS TREATMENTS COMPARED TO AVERAGE NEW BLADE LIFE[8]**

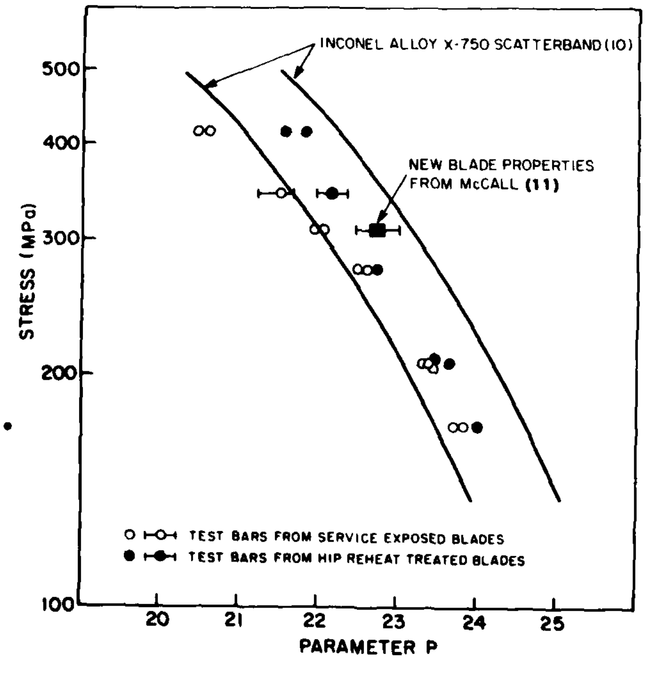


**FIG. 12: LARSON-MILLER PLOT ($P = T \times 10^3 (20 + \log t)$, T IN °K, t IN HOURS) COMPARING STRESS-RUPTURE PROPERTIES OF SERVICE-EXPOSED, VIRGIN AND HIP PROCESSED BLADES[8]**

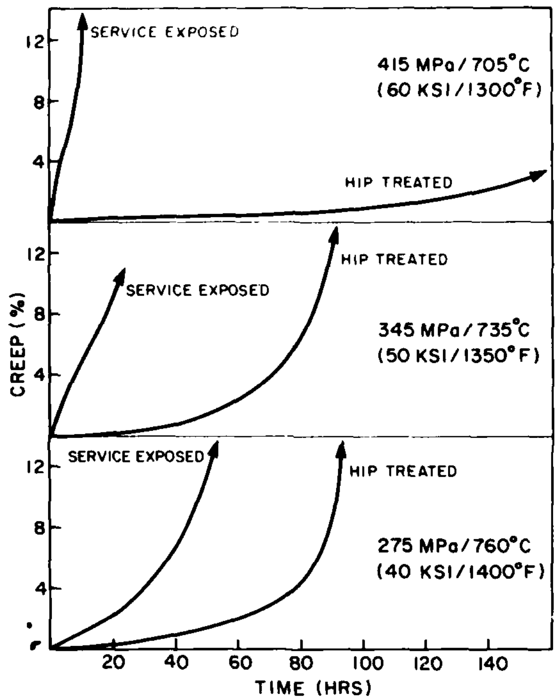


**FIG. 13: CREEP RUPTURE CURVES COMPARING THE SERVICE-EXPOSED AND HIP REHEAT-TREATED CONDITIONS AT THREE STRESS/TEMPERATURE COMBINATIONS[8]**

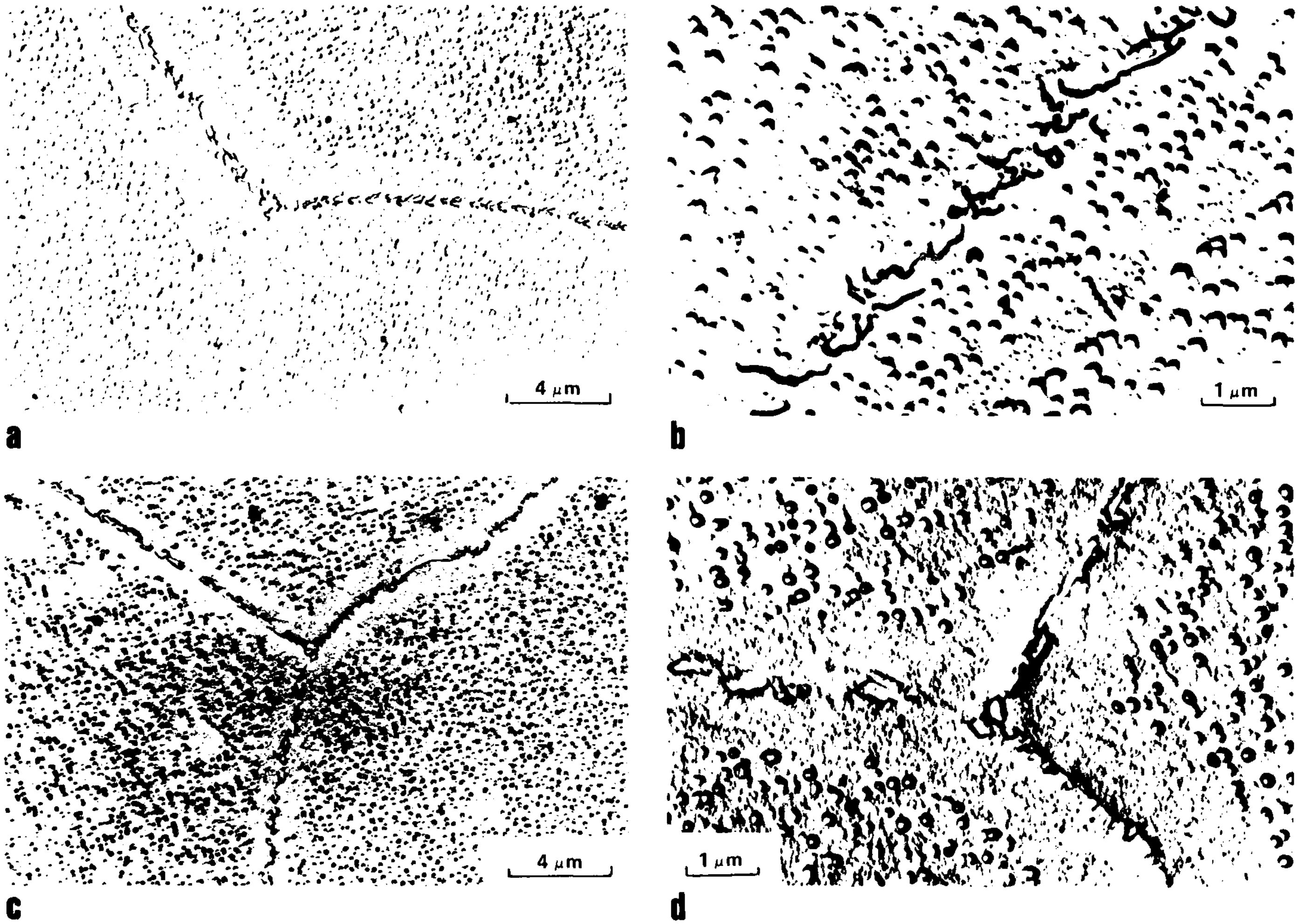


FIG. 14(a) and (b): MICROSTRUCTURE OF SERVICE-EXPOSED INCONEL ALLOY X-750 BLADES. THE GAMMA-PRIME PARTICLES ARE STILL SPHERICAL AND ONLY SLIGHTLY COARSENED AND GRAIN BOUNDARY CARBIDES FORM CONTINUOUS FILMS. (c) and (d): AFTER HIP PROCESSING, THE GAMMA-PRIME AND CARBIDES ARE REFINED AND A GAMMA-PRIME FREE BAND APPEARS AT THE GRAIN BOUNDARY[8].

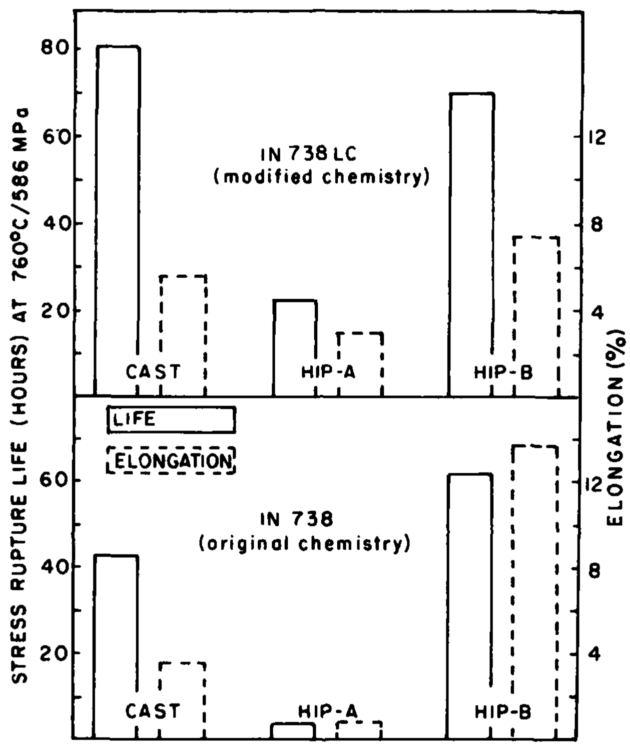


**FIG. 15: COMPARISON OF THE AVERAGE 760°C STRESS-RUPTURE PROPERTIES OF IN-738LC AND IN-738 CTS BARS IN THE AS-CAST AND HIP CONDITIONS, (MODIFIED CHEMISTRY: LOW CARBON, LOW ZIRCONIUM)[7]**

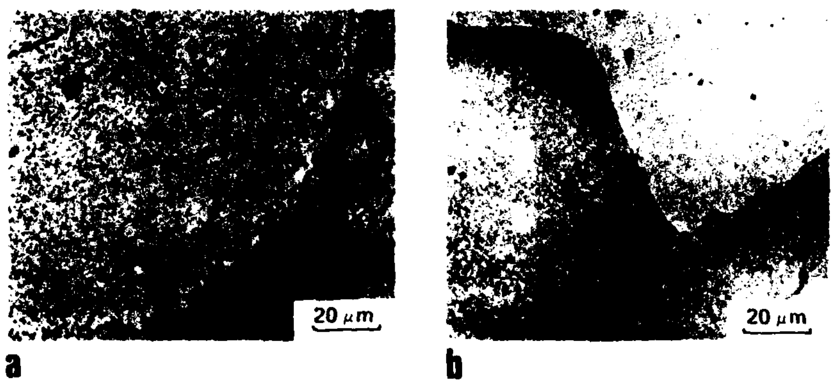


FIG. 16: GRAIN BOUNDARY STRUCTURES IN CAST AND HIP PROCESSED IN-738. NOTE THE FINELY SERRATED GRAIN BOUNDARY STRUCTURE IN HIP-B PROCESSED MATERIAL (OPTICAL MICROGRAPHS OF SAMPLES ETCHED IN 2% BROMINE IN METHANOL)[18].

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To reduce these costs and also to conserve strategic materials, efforts are being expended to develop treatments that will allow used parts to be refurbished and returned to service. This paper reviews some of the work done in this area in Canada with particular emphasis on rejuvenation of nickel base superalloy blades and vanes by hot isostatic processing. The limits and prospects of this approach are discussed.

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